MAPPING DEFORESTATION AND LAND USE IN AMAZON RAINFOREST USING SIR-C IMAGERY

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Abstract

Land use changes and deforestation in tropical rainforests are among the major factors affecting the overall function of the global environment. To routinely assess the spatial extend and temporal dynamics of these changes has become an important challenge in several scientific disciplines such as climate and environmental studies. In this paper, the feasibility of using polarimetric spaceborne SAR data in mapping land cover types in the Amazon is studied. SIR-C/X-SAR data acquired in 1994 over the area of Rondonia, Brazil where the. land use changes rapidly, have been used in delineating land cover types and deforested areas. Here, the. emphasis is placed on several clearing practices and forest regeneration that can be characterized by using the sensitivity of SAR channels to vegetation biomass and canopy and surface structure. A supervised *maximum a posteriori Bayesian* classifier is used to identify primary forest, secondary fore.st, pasture/crops, quebradao, and disturbed forest by using the L- and C-band polarimetric data. The results are verified by using data from the. field survey and by comparison with the Landsat data acquired in August of 1994. It is shown that the SAR data can delineate these five classes with approximately 72% accuracy. The confusion arises when separating the old regeneration from primary forest and the young ones from crops or fallow regrowth. Quebradao with scattered trees over pasture or forest regrowth is also confused with the secondary and disturbed fore.sts. The difficulty in separating these land cover types is related to the dynamics of land use changes in the region and the lack of a unique definition for land Cover types. It was found that Landsat and SAR data carry complementary information about the vegetation and surface characteristics that, when used in synergism, can increase the classification accuracy. By reducing the number of land cover types to three classes including primary forest, land use (pasture and crops) and regrowth/disturbed, the accuracy of classification increased to 87 %. A dimensionally analysis of the. classifier showed that the combined L-band HH and HV polarizations were the best polarizations for mapping the three classes that produced an accuracy of 94%. Through the analysis of SIR-C data acquired in April and October of 1994, it was found that deforestation and temporal dynamics of the, land use change can be mapped by multi-temporal SAR data.

Introduction

There is a genera agreement that out of 15 million square kilometers of tropical forest that may have been existed once according to the bioclimate data , there is less than 9 million left (A4 yers,1988). The destruction of tropical rain forests has been going on for a long time, dating 3000 years ago in Africa, 7000 years ago in South and Central America, and possibly 9000 years ago in India and New Guinea (Flenley, 1979). initially, the clearance of forest by indigenous inhabitants were small scale and had little impact on the structure and functioning of the rain forest ecosystem, and if it did so, it had localized effect. The main exploitation of the predominantly wet tropical forest is more recent and it has prompted by various economic ant] survival episodes from the early part of the nineteen century and accelerated in the past few decades(Hecht and Cockburn, 1989). Deforestation in the Brazilian Amazon, as the largest continuous region of rainforest in the world, has received more attention, mainly due to its effect on the species dive.rsity and its impact on the global climate and atmospheric chemistry. According to Shukla et al (1990), rapid destruction of vegetation in Amazonia can bring large scale and irreversible changes in the region's hydrological cycle and climate.. Dickinson (987) also estimated that the transformation of the Amazon forest biomass is responsible for 10-1 5% of the total increase of carbon in the atmosphere.

The causes of deforestation and changes in land use is the focus of a variety of investigations that expands from forest sciences and ecology to economic, socialand anthropological studies. Even though, the literature is diverse, there is a general agreement that the. rate of deforestation is influenced by several factors, among them,the colonization programs, legal systems of land tenure, relation of natural resources ant] production systems to market variables and capital accumulation (Hecht,1993; Moran,1984). Large scale deforestation in Brazilian Amazon began with the construction of Belem-Brasilia highway in 1958. Despite the slow occupation of the. land along the road in the beginning, by introducing the program of national integration in 1 97 1, and the construction of the

Tranzamazon highway, transforming the forest to pasture for cattle ranches and agricultural practices increased rapidly. As a result, in the past 20 years, deforestation increased in the Amazon basin, especially in regions such as Rondonia, Acre, Mato Grosso, Para, and Maranhao. One of the largest settlements in Amazonia was the Polonoreste program in Rondonia which began in 1982. The program included the designation of large areas of colonization and the construction of roads. At the onset of the program only 2% of the state was deforested and by 1991 it increased to 14.5% the, highest in the entire Amazon basin (INPE, 1992).

Recent estimates of vegetation clearing in Brazilian Amazon indicates that by 1991, the total area cleared has reached 426,()() km^2 (1().5% of the original] y forested portion of Brazil) with a annual rate of approximatel y ?2,()() km^2 over 1978-1988 period, 14,()() km^2 for 1989-1990, and 19,()(K) km^2 for 1990-1991 (Fearnside, 1993). The main source of information for such estimates have been remote sensing data availability in the past twenty years. Some of the pioneering work in constituting a systematic monitoring capability and quantitative techniques have been performed using the Landsat imagery (Skole and Tucker, 1993; IN])]{, 1992). Satellite data have proven to demonstrate where deforestation is being taken place and how earlier estimates measured by field survey have been erroneous. As the technology for sate.llitc surveillance has improved, developing new methods for capturing the sensitivity of deforestation to small land use changes within short time intervals is in order. Despite exalting results in routinely estimating annual rates of deforestation with Landsat imagery, difficulties of obtaining more frequent data over areas where. continuous cloud cover obscures the ground, inconsistent means of delineating secondary forest from primary forest and/or from various practices of forest disturbance and clearing, suggests that accurate land use and deforestation mapping is still a scientific challenge. Spaceborne radar systems are potential tools for resolving some of the ambiguities inherent in results based on measurements in optical regime, partially because of their insensitivity to cloud cover and the capability to penetrate the vegetation layer.

Current results indicates that multifrequency polarimetric radar systems are ideal for discriminating vegetation formations, estimating above groundbiomassinsecondary forests and monitoring the dynamics of deforestation in Amazonia (Foody, 1994; Terborgh, 1 992).

This paper reports on the use of spaceborne polarimetric radar in mapping land use and deforestation in Amazon by analyzing the high resolution SIR-C L- and C-band data over an area in the state of Rondonia. Our objective is to explore the feasibility of using radar data in accessing the dynamics of land use change and to complement the existing annu al mapping capability of Landsat imagery. Therefore, we concentrate on discriminating five major land cover types: primary forest, secondary regrowth, pasture/crops, quebradao (forest clearing except large trees) , and disturbed forest (e.g. selective log ging, clearing of vines and understory). We start by discussing the sig nificance of each land cover type and the rati onale for choosing them as labels in the classification procedure. A supervised *maximum a posteriori Bayesian* classifier is then employed to separate the classes. The accuracy of the classified map is discussed based on the performance of the classifier over training areas, field survey data, and characteristics of class types as seen in Landsat imagery, In order to enhance the. accuracy of classification and to examine the usefulness of the, SAR imagery for mapping deforestation, we generated a new map by reducing the number of classes from five to three (forest, nonforest, regrowth/d isturbed). Finally, the April arid October SIR-C data are analyzed to understand the changes of hind use in the region. The possibility of using the current space.berm radar systems for mapping deforestation and the synergism between Landsat and polarimetric SAR data to achieve a better accuracy in mapping land use changes are discu ssed,

Study Area

Rondonia, Brazil was chosen for this study because of the importance of dynamics of deforestation, land use practices, andthe availability of field data. Rondonia is located in the south central Amazon basin and covers an area of 243,000 km^2 (1 'igure 1). Large scale deforestation in this area began with the construction of Transamazon highway in 1968. Road building was part of a larger colonization program that started in 1971. The goals of this program was to move families in the Amazon basin and to service them a with network of settlements and communities that in turn was supposed to improve standard of living, to promote economic growth, and to encourage Brazilians to occupy the Amazon in particular near the borders (Moran, et al., 1994). By providing short term loans, subsid its, and tax incentives, the government encouraged the farmers to move in this region and produce annual and perennial crops and beef. As a result, conversion of forest began rapidly as farmers and cattle ranchers cleared the forest for cultivation and pasture. The lack of transportation means in Rondonia also created obstacles for access to markets and obtaining services for the colonists. '1'0 meet this need the main highway through Rondonia, BR-364 was paved without any programs for the control of deforestation. The road, therefore, became an avenue for the colonists to move into the stale and cutting the intact forest near the road. 'J'here arc growing reasons to believe that the massive deforestation did not help the economy of the region and in fact it lead to rural depopulation in the region because the forest clearing did not produced sustainable long term agricultural and range lands (Moran, et al., 1994). Timber production and mining were two other important factors in deforestation. In Rondonia, with very fcw tree species being harvested, wood products account for (')()% Of the industrial output. The rate of deforestation in the region depends on all above mentioned factors and the reader is referred to Skole and Tucker, (1993), Fearnside, (1993), and INPE, (1992) for recent estimates of deforestation in the region based on remote. sensing data since 1978.

Field observation and historical data indicates that forest disturbances in Rondonia were. systemat ic and showed various types of coloni zation practices in the region. Forest clearing occurred at different scale.s and majority of forest clearings 1()()-ha in size arc used for crop cultivation or pasture. Disturbances of greater than 1()()()-ha arc rare and are mainly used for range lands combined with small agricultural holdings. in general, after clearing the forest is replaced by managed pasture, annual perennial crops, regrowth forests on abandoned pastu re and croplands. The turnover time for these changes are short and may vary depending on the land tenure.

Remote Sensing and Field Data

During the April and October 1994, a polarimetric L-, C-, and X-band synthetic aperture radar system (SIR-C/X-SAR) wa s laun ch ed on the space shuttle Endeavor for two ten day missions. The characteri stics of the system are given elsewhere in this journal and in an overview by Evans et al. (1994). The advanta ge of the SIR-C/X-SAR system over its earlier generations and the current spaceborne satellite radar systems such as ERS-1 and JERS-1 is mainly its three dimensional illumination parameters (wavelength, polarization, and angle of incidence). Even though, both missions were short, they provided a large amount of data with different instrument and orbital parameters that arc. being explored in various disciplines. During both missions, shuttle radar collected data over a large part of the Brazilian Amazon for a variety of applications such as dc.forestation, land use, biodiversity, and inundation studies (1 less et al., 1 995). The images over Rondonia are taken on orbit number 23.5, with 32.0 degrees incidence angle, and 50 km swath in a dual polarization mode (L-, and C-band, HH and HV polarizations). The nominal resolution of the data at ?() MHz bandwidth is approximately 25 m. in this study, wc have concentrated mainly on the data acquired On October 1, 1994 within 45 days of a cloud free. Landsat image acquired on August 15, 1994. Figure 1 shows the state of Rondonia and a segment of the SIR-C swath used in this study. The April data were also classified in order to illustrate the dynamics of the land use change in the region. The calibration of the radar data was performed using relative and absolute calibration procedures in order to establish a relationship between the image intensity and the radar backscattering coefficients of the image surface. During the. mission, several trihedral corner reflectors were deployed along

Amazon transect data takes near the city of Manaus. Once the calibration constants of the system over the external targets were calculated, the images were calibrated routinely within the frame. processor. The absolute calibration of the SIR-C data was found to be within -i/-2 dB or better for both 1,-band and C-band image data. Figure 2 shows the study area as imaged by the S1 R-C radar and the Landsat TM. The SIR-C image is a color composite of three channels, 1,1111, LHV, and CHH and the 1 andsat image, of three bands, 5,4, and 3. The Landsat image is registered to the SIR-C image and is resampled to 25 meter resolution.

One the most critical aspect of land cover mapping is the field data acquired on the ground for the validation of the remote sensing data. In choosing specific silt.s for field survey and ground measurements, several factors need to be considered: 1) the sites must be accessible., 2) the sites must be large enough and follow the general patterns of land use practices in the region, 3) the field measurements must coincide with the satellite overpass since forest clearing, crop harvesting, and forest fires can occur in short time scales (days or weeks), and 4) each site need to be surveyed with the knowledge of the sensitivity of the SAR signal to various vegetation scattering mechanisms.

During the month of October, 1995, a year after the SIR-C/X-SAR mission, a group of investigators from INPE (Instituto Nacional de Pesquisas Espaciais) conducted field survey and ground level data collection in an area covered by Landsat images that also overlapped with the SIR-C data used in this study. The data collection included field observation of large areas of land use for pasture and crops, secondary forest, and Quebradao. '1'0 characterize, the primary and secondary forests in the region, several sites were chosen for tree dbh, height, density, and canopy LAI (leaf area index) measurements. Although these were collected for different research objectives than from those of the present study, the field surveys and the experience gained from their collection helped us verifying land cover classes and understanding the information content of the SIR-C and 1 andsat image data. Campbell and Browder (1995) have noted the effectiveness and problems associated with the field data collected in Rondonia for remote sensing image analysis. Some of their observations apply directly to the field data used in this study. Among them, few are particularly relevant: 1) the timing of th e field data collection and survey does not coincide with the acquisition of the satellite imagery. The rapid rate of forest regeneration and short term land use decisions may cause changes in the amount of vegetation on a particular site that can greatly influence the backscatter return or spectral responses of optical sensors, 2) land cover is not always homogeneous with respect of the class type and there are often variations within fields that may cause mixed pixel information entering in the sites used as training areas for classification, 3) in Rondonia, field sizes arc usually small and features seen on the ground may not be visible in the image data due to the effective resolution size of remote sensing sensors, and 4) typology and semantics used in labeling land cover classes arc not universal and depend on the local terminology used by farmers or the type of socio-economic surveys used in each region. These problems will affect the assessment of the accuracy of any classified map but may not be quantified easily.

1 ,and cove]" Types

The labeling of land cover types used in this study is tied with the local conditions of the region and the usefulness of the classification results for two types of applications: 1) for understanding the local land use changes that can be meaningful to farmers and policy makers, and 2) for incorporating into a larger scheme of land cover types in the tropical ecosystem studies where the main objective is the biomass (distribution and carbon exchange with the atmosphere. In both applications, the general tendency is to arrive at detailed segmentation of vegetat ion and land use type that may or may not be achieved by a remote sensing instrument. 1 lowever, in our context, wc limited ourselves to conventional classes that are used in many studies and appears to be widel y accepted (Campbel l and Browder, 1 995). Wc have limited the classes to five land cover types: primary forest, secondary forest, pasture/crops, Quebradao, and disturbed forest, These class types were chosen due the.ir importance in the above mentioned applications. Another recurring problem arises from the limited field data collection in the region for any comprehensive characteriza tion Of land cover classes. Even though, there have been several field studies in the region of Rondonia, the data published in the. literature arc conducive to misinterpretation since they are aimed at different objectives, and for reasons mentioned earlier.

Primary forest :

By primary forest, in this study, wc refer to the intact tropical humid lowland forest. This class of forest is a complex mosaic of various phases of regeneration, accumulation and decay of biomass and structure. The diversity of plants at different successional stages depending on the soil type, growth rate, life cycle, phenology and physiological characteristics make the primary forest an extremely difficult unit to dissect. Even though within the primary forest, various microclimactic ecotones, leafing rhythms, and heterogeneity of soil, water availability, and local relief characteristics can introduce pronounced variabilities significant for ecological and botanical investigations, in land use and global carbon cycle studies it can be considered as one unit (Detwiller and Hall, 1988). Furthermore, by choosing the primary forest as one class, the land use change is often referred to as the conversion of forest to other types of land cover such as crops, pasture, logged and secondary regeneration. This would imply that by calculating the carbon Content of the primary closed forest and mapping the conversion of forest into other land use, one may be able to model the rate of carbon exchange of tropical reg ion with (he. atmosphere (Brown and Lugo, 1984, 1990). For example, Detwiller and Hall (1988) estimated that the use of forest soil for agriculture anti pasture reduced their carbon content such that converting the forest to permanent agriculture and pasture (ice.rcascs the soil carbon about 40 and 20 percents respectively (Detwiller and Hall, 1988).

Secondary forest (Capoeira):

Secondary forests cover more than 600" million hectares of tropics] rainforest and are often created by human activity (Brown and Lugo, 1990). After forest is cleared for agricultural, pasture or for forestry purpose, the processes of secondary succession begin shortly after the land is abandoned. The land use preceding the secondary regrowth include slash and burn practices and shifting cultivation with cycles lasting between one to three years. In tropics] region, the early stages of succession are characterized by a very dense undergrowth with weedy herbaceous plants and fast growing vines. The rapid growing of early colonizers are due to the seed distribution in the soil immediately after the disturbance.. The initial herbaceous phase often does not last very long and the plants die within a year allowing the vines grow with the woody pioneer species, and within few years, the combination form a nearly closed canopy (Ewel, 1 977). During the successional stage, several forest attributes such as biomass and leaf area index increase rapidly that make the secondary regeneration a viable area to be detected by remote sensing techniques (Foody and Curran, 1 994). The leaf area index and woody biomass reach a maximum after 20 and 40 years respectively making the secondary forest difficult to separate from the primary forest. The productivity of the successional forest depends cm several factors such as the length of dry seasons, how long after the disturbance the land was abandoned, and whether the secondary forest is being disturbed continuously. The regrowth process has also several stages that can influence the structure. of secondary forest and therefore its productivity and tots] biomass (Budowski,] 965). In wet tropics] areas such as Rondonia, the process of regrowth includes a very wide distribution of fast growing natural species forming a dense layer of forest canopy that can glow up to 5-8 meter in three years. This layer, if not disturbed or burned, can grow up to 15 meter by the age of 1 (). It has been Observed that most secondary forests reach their maximum leaf biomass early in the.ir development and maintain these values till they mature (Brown and Lugo, 1990). These forests do not necessarily have high woody above ground biomass (< 1 ()() tons/ha) for ages less than 1 0 years old, however have a large amount of leafy vegetation, lianas, and herbaceous species that do not play a role in biomass calculation but may have strong scattering or absorbing effects on the. SAR signal. '1'bus, the identification of secondary forest does not necessarily rely on the biomass values of these forests but the.ir structural information. Figure 3, shows the process of recovery of a primary forest after it has been cut and the typical range of production of woody biomass.

Pasture/Crop s:

Conversion of forest to pasture is one of the most common processes of deforestation in Amazon, where cattle grazing dominates the land use. Logically, the incentive for clearing large areas of forest for pasture is the lucrative market for cattle and beef, the so-called "hamburger connection" (Hecht, 1993). This conversion is also considered one of the main sources of carbon release into the atmosphere. Pasture like crops does not remain productive in most areas of Amazon because of the low level nutrients left in the soil after clearing and degradation due to rainfall and surface runoff. Some pasture lands are burned or fertilized for temporary new growth, some are abandoned that eventually either turn into forest regrowth or unproductive bush fallow or secondary regeneration. The size of the pasture cattle ranches in Rondonia also varies depending on the projects that encourage or subside them. Most of the highly subsidize operations involve. large scale clearing of tile. order of 10,()()[) ha, where as the non-subsidize ones are in smaller scales. A large part of Rondonia, specially within our study area is covered by small and medium size rant] ies (100- 1000 ha).

Another scheme for deforestation in Amazonia is to create land for plantation and agriculture. in Rondonia, like other parts of Brazilian Amazon, several projects associated with colonization and agrarian reforms have provided incentives and short term loans for raising annual crops such as corn, beans and rice.. The pattern of farming practices depends on the soil type for Rondonia has been selected for colonization mainly for its good soil compared to other parts of Amazon. However, after few years, the soil is depleted from its natural nutrients and the crop lands are abandoned that often arc turned into secondary forests. Therefore, areas under plantation and fanning arc transient and any monitoring and mapping activity must be updated regularly. This also increases the probability of error in historical survey and field data for generating maps of land use characteristics in the region. Given the. dynamics of land usc change for crops and plantations, it appears that identifying areas under active agricultural practice by remote sensing techniques can benefit both socio-economic policies and global ecosystem studies that depend on the knowledge of land form conversion. The type of crops and plantations can also vary depending on the soil type. The less nutrient and unsuitable soil is abandoned quickly and is covered with pasture Or weedy vegetation. Areas covered by perennial crops such as coffee, rubber, cocoa, fruit, and bananas differ by soil type. Coffee is considered a major perennial crop, both in terms of area planted and received income, and are planted on moderate soils (Dale, et al., 1 993). It appears that in Rondonia, the annual crops arc less dependent on soil type. Due to limited field data for classifying various crops and the fact that most of the fields were harvested or burned in October, 1994 at time of SIR-C mission or October, 1995 at the time of field work, we choose only one label for pasture and crops. The label includes abandoned and nonproductive fields as well as the active cattle ranching agricultural fields within the study mea.

Quebradao:

Quebradao means broken down in Portuguese and it refers 10 a stage of deforestation by mechanized logging and clearing where the large trees arc left intact. After logging, these areas arc often covered with pasture for cattle ranching while large trees provide shade for cattle and prevent soil erosion. Field observation shows that quebradao appears as pasture lands with standing trees 5 to 20 meters apart. Like other forms of deforestation in the region, the destiny of quebradao depends on the further land use practices. in some cases, the land is abandoned for a long period before any plantation or further clearing, providing a capacity for succession back to forest or left as a wasteland overgrown by weeds. In other words, quebradao is an intermediate stage of deforestation from intact forest to pasture or agricultural land use. Soon after clearing, quebradao has a distinct spectral properties both at radar and optical imagery that can be visually discriminated from total clearing and slash and burn areas, thereby a reasonable candidate for a land cover class label.

Disturbed Forest:

in Rondonia like other regions of the tropical rainforest, exploitation of the forest are manifold and complex. Besides total deforestation that have degrading impacts on the forest, there are other anthropogenic factors, as a result of socio-economic conditions, that can affect and alter the species diversity and induce irreversible changes in the forest ecosystem. Among the man-induced disturbances in the tropical forests, selective logging by hand, extraction of timber with the aid of saw chains, silvicultural measures that kills non-commercial species in favor of commercial ones, tree tapping, cultivation of crops by removing the forest understory, and browsing at the ground level by domestic cattle which prohibits natural regeneration are the most important ones. Identifying, mapping, and monitoring areas of these disturbances can improve our understanding of patterns of land use changes and the frequency of degradation in tropical region. For example, in Rondonia, being of the most actively disturbed region in the Amazon basin, any future changes in the land use is a continuation of changes in the. past. Therefore, separating areas of most stable and intact forest from areas of damaged, unstable, and modified forest will set some standards for assessing the history of land use change. Since identifying the type of disturbances in the tropical forest by remote sensing techniques requires intensive field survey and image analysis, in this study, we limit ourselves by using only one label to distinguish the disturbed or damaged forest in the SAR image. The label refers to disturbances that arc due to clearing of vines and understory which leads to selective logging and eventually to total clearing of the forest after a short time. At this moment, it is not clear weather the SIR-C data can distinguish areas undergone selective logging or are under silviculture measures. in the SAR image shown in Figure 2, bright areas predominantly refer to areas of disturbed forest where due to the slight sparseness of vegetation relative to the neighboring primary forests, the t-alar backscatter has increased. Since at the time of the data take, the top layer of the forest canopy was still intact, the disturbance does not show up in the Landsat images.

Classification Methodology

Several classifiers designed for polarimetric radar imagery are currently available in the literature. In this study, we have used a *maximum a posteriori Bayesian* (MA f') classifier to perform a supervised classification of the SIR-C data. The theory has been described in details elsewhere (Rignot and Chellappa, 1992; Kong et al., 1988; Saatchi and Rignot, 1995). The MAP classifier is an extension of the *maximum likelihood Bayesian* (Ml,];) classifier in that it dots not assume equal *a priori* probability for the image classes. In this approach the SAR amplitudes are modeled as circular Gausian distributions which implies that the textural variations in the radar backscatter data are assumed to be insignificant. 1 'rom modeling the *a priori* distribution of SAR data and the image classes a model for the *a posteriori* distributions of classes are obtained using the Bayes theorem. In other words, MAP classifier views the classes as random variables with some *a priori* distributions and then re.vises the decision criteria through an iterative procedure to optimize the decision about the nature of classes,

The learning procedure for the classifier is supervise.d in the sense that the class labels are known in advance and training areas are chosen based on the *a priori* knowledge of the scene or visual interpretation of the image with the help of data obtained through the field survey. Since the SIR-C radar data used in Ibis study were acquired in mode. 1 1 with only two polarizations to accommodate for wider swath, the polarimetric classifier has been modified to work with the individual channels instead of the fully polarimetric covariance matrix. To implement this technique, we first define the *a priori* distribution of classes from the training areas. According to the importance of the land cover types described in the previous section, wc concentrated on 5 classes: 1) primary forest, 2) secondary regrowth, 3) disturbed forest, 4) Quebradao, 5) pasture/crops. For each category, we selected large fairly homogeneous sites as training sites, In some cases such as primary and secondary forests, we have used more. than one training area in order to include natural variations of radar signature of primary forest due to the topography and slope effects and the biomass (or age) variations of the secondary forests, Table 2 lists the average and standard deviation of the calibrated radar backscatter coefficients for the 6 training areas (young and old secondary regrowth are separated). For each training area a polygon is defined in order to maximize the number of pixels in the average and exclude the edge effects from other classes,

in the SIR-C imagery, the incidence angles over the entire swath is constant (3?.1 degrees) and thereby unlike airborne systems the radar parameters for the image classes arc assumed to be independent of incidence angle variations. The classifier is sensiti e to the mean values of radar backscattering amplitudes over training areas and assumes tha [here is no correlation between various channels.

Results and Discussion

Mapping of the land cover classes was first performed using the training areas for the classes described in Table 1. The results of this classification is shown in Figure 4 where the young and old secondary regrowth are combined to form one class, All four channels of the SIR-C data (1 .HH, LHV, CHH, CHV) were used to produce the classified map, since theoretically including all available polarimetric channels can yield the highest accuracy. This initial classification resulted in poor accuracy for the secondary forest, pasture/crops and Quebradao. The classification accuracy for each class is determined by measuring the number of pixels correctly classified into the class divided by the total number of pixels in that class and is illustrated in the form of confusion matrix in Table 2. The elements in the confusion matrix are calculated for seven known sites for each class that also included the training areas. For pasture/crops over 71 % of pixels were classified accurately. However, as the map over the entire image was compared with the Landsat and the field survey, it was found that several pasture fields depending on their growth stage and possible regeneration of other species were confused as secondary regrowth. The confusion turned out to be high enough to conclude that due to the limited channels of the SAR data and the field survey in the entire region covered by the image the separability between young regeneration and pasture is difficult. It is noteworthy to mention that other factors such as fire practices in some pasture and crop lands and young regrowth before the. acquisition of the image in October may have. also contributed to this confusion.

For delineating the secondary regrowth, we achieved only 62% accuracy ('I'able 2), while the remaining pixels were classified as primary forest or quebradao. 1.1 IV was the determining channel in separating the secondary forest from primary forest because of its sensitivity to biomass variations. It was surprising to realize that this channel could not distinguish old secondary forests (> 6 years) even though the biomass levels did not reach (100 tons/ha), which is often referred to as the maximum biomass 1.-1 IV is sensitive to (Dobson, et al., 1992). The reason is that woody biomass is not the best indicator of the regrowth stages in the tropical forest. in secondary regrowth, the plant density is high and the forest floor is covered with different species at various successional stages and even though the number of large trees is not high, the total amount of green vegetation (radar backscatter data are directly sensitive to the tots] above ground vegetation moisture) that often dots not contribute to the calculation of the total above ground biomass (biomass is usually calculated for trees with dbh> 5 cm) is enough to saturate the radar backscatter.

The same trend was also observed in separating, the disturbed forest from the primary forest. Due to the microtopography in the region some pixels on the slopes facing the radar look direction have higher backscatter than the ones with opposite slopes, causing changes in the LHH return that was the key channel to distinguish disturbed forest. The LHH backscattering coefficient is sensitive to the double bounce scattering mechanism that is often enhance.ci when the understory is removed. Similar phenomenon could have also contributed to the error in separating quebradao from disturbed forest. In addition, some areas of quebradao with pasture regeneration were confused with the secondary regrowth.

To further analyze the separability of vegetation classes, wc used bivariate distribution of backscattering coefficients for each class on the SAR data feature space! (Figures 5). The backscatt er values used in this analysis were collected from SAR data over seven sites selected over the entire area by visually verifying each class from Landsat imagery and the field data. Figure 5a shows the class separability in two dimensional space of LHV and CHV. In this space, pasture, crops and Quebradao arc easily separated whereas the primary, secondary and disturbed forests have major overlaps. Both CHV and LHV channels arc sensitive to volume scattering within the forest canopy, therefore, having small dynamic ranges over forested areas but widely distributed over low vegetation and Quebradao. Disturbed and secondary forests arc well separated in LHV-LHH Space but are distributed closely with an average distance of 2 dB along LHH axis and about 1 dB along LHV axis (Figure 5b). Disturbed forest and quebradao have higher LHH return due to the enhanced double bounce scattering resulted from clearing the forest floor anti sparsely distribute] trees respectively. C-band channels, being saturated over forested areas can contribute in separating lower vegetation types as shown in Figure 5c. In fact, by changing the dimensionally of the classifier (i.e. reducing the number of elements in the covariance matrix of each pixel), it is found that CHH and CHV channels help delineate the low vegetated areas but slightly removes the distinction between the forest types achieved by LHH and LHV.

Thus far the analysis has shown that with four channels of the SAR data, five major land cover types can be separated with an average of 72% accuracy. Given the above mentioned problems in the field data collections and the diverging definitions used in land cover types used in this work and previous studies such as Skole et al. (1 994), it is difficult to verify the classification results over the entire image or for large scale studies. We have reduced the number of classes in favor of more common class types and increasing the accuracy of classification results. We found that by using only three classes of primary forest, regrowth/disturbed, and pasture/crops, not only the genera] patterns of the land use in the region can be captured, but the resulting classified map will be more appropriate for comparison with similar maps generated by other investigations. To achieve this goal, we performed the classification by combining the backscatter characteristics of training areas of disturbed forest with regrowth, tine] quebradao with pasture. A new confusion matrix computed for these three classes is shown in "Table 3. The overall accuracy of the classification increased to 87% with higher separability of regrowth/disturbed from pasture and from the primary forest, The results also implies that areas of cleared forest (past ure/crops) are. easi 1 y separated from forest areas, suggesting that SAR data are suitable for deforestation studies.

By reducing the dimensionally of the classification, meaning reducing the number of channels used in the classifier, we have determined the added values of various channels of SIR-C data. The results show that L-band HH and HV polarizations are the best channels for separating the three classes (Table 4). In fact, the classification accuracy increased to 92% by using the L-band data only. The reason for this is that the L HV easily separates the low vegetation such as pasture from the forested areas and the combination of LHH and L HV can separate the, secondary regrowth from the primary forest with almost the same accuracy as obtained with all channels combined. According to "Table 1, the C-band backscatter dynamic range over forested areas is less than 3 all], implying that C-band polarizations are not useful in separating fore.st areas. in genera], when one radar channel dots not separate to image classes, it acts as a noise source to the classification and increases the probability of error. Other combinations such as 1,1111, (1.1111,(3111), (1.1 IV,CHV), and (I ,11}1, CHH, CVV) performed poorly and produced classification accuracy of approximately 60%, 62%, 66% and 540/0 respectively.

To address the dynamics of land use change, we classified the SIR-C data acquired in April during the first shuttle mission with the same backscatter characteristics gathered over training areas from the October data set. The results are shown in Figure 6, with the three channel color composites in Figure 6a and their respective classified images in Figure 6b. Some of the areas of land use changes between April and October are delineated in Figure 6a. These figures draw attention to the direction and magnitude of changes in the region. During April, being the rainy season in Rondonia, the backscatter responses of pasture and crop fields are higher than October due to the increased soil moisture and the availability of crops. Whereas in October, being the dry season, soil moisture is low and majority of crops are harvested or pasture fields are burned for the next cycle of cultivation. Moreover, most of the logging and forest clearing are conducted during the dry season, making both images useful in understanding the pattern of deforestation in the region. A simple, comparison between the two images indicate that within the 2400" km^2 area covered by the image, approximately 19.3 km^2 has experienced deforestation or forest disturbance of some kind, This implies 0.8% change in the area covered by the primary forest which is about the, average annual rate of deforestation in Rondonia reported by 1 NPE (1992).

Summary and Conclusion

The results presented above suggest that polarimetric SAR data can be used over tropical rainforests for land use and deforestation studies. A MAP classifier applied to all polarimetric SAR images (1.1 II 1, LHV, CHH 1, CHV) was able to separate five classes of land cover with 72% and three classes with 87% accuracy respectively. The combined L-band HH and HV data could achieve 94% accuracy with three classes, suggesting that the low frequency radar systems are more appropriate in distinguishing land cover types in tropical rainforest. It is found that the problems that one encounters in interpreting the field data and typology of land cover class labels in tropical forests arc important factors contributing to classification errors. The difficulty arises particularly in separating secondary regrowth and disturbed forests from the primary forest. The 1 .-band radar response appears to saturate at less than 10 years of regrowth. Unlike temperate or boreal forests, where the signal saturation is dependent of the above ground woody biomass, in tropical forest tbc early saturation of the signal is attributed to the amount fresh biomass or water content in the forest canopy. The fresh biomass includes leafy vegetation of overstory, understory, vines, and lianas that do not usually contribute to the calculation of the woody biomass. However, since the objective of the study was not biomass estimation, wc can not assess the performance of radar channels for estimating secondary forest biomass. Furthermore, the difficulty of separating old secondary regrowth from the primary forest can be improved by incorporating additional features such as texture 01" P-band frequency in tbc classifier, From our classification results and dimensionally analysis, wc predict that the current spaceborne single polarization SAR systems are not suitable for mapping land use in tropical forests. The JERS-1 1 -band HH polarization data can produce above 60% accuracy for three land cover types if other features such as texture are also added to the classifier. Unlike in the boreal forest where a combination of JERS-1, RADARSAT, and 111< S-1 could resolve the differences between major forest types with 80% accuracy (Rignot et al., 1994), in our study, the accuracy was worse than JERS-1 or the. combination of JERS - 1 and RADARSAT.

comparison of the April and October SIR-C images and classification showed that the anthropogenic activities in the region affecting the land use can be mapped by multi-temporal data. This result is quite expected in the Amazon basin where both seasonal cycles (rainfall rates) and the pace of land use activities dramatically vary in the region.

The two SIR-C data sc(s arc taken in rainy and dry seasons respectively and demonstrate di fferent surface moisture, amount of crops, and past present in the area.

Finally, the comparison of Landsat and SIR-C data over the study area indicates that Landsat and SAR data provide complementary information about the land use and forest fragmentation. in Landsat imagery, areas Of low vegetation such as crops and pasture, young regeneration, and quebradao are easily distinguished from the primary forest. On the other hand, the old secondary regrowth and disturbed forests can be visually separated from the primary forest. One of the most interesting observations is that some areas of secondary regrowth appear in the Landsat images but arc not clearly visible in SAR images. WC hypothesize that in these areas, the secondary forest has different leaf structure and color than the primary forest and therefore different spectral characteristics that show up in Landsat images, whereas the SAR response, in particular at 1.-band, which is averaged over the depth of penetration in the forest canopy, the backscattering coefficient is not sensitive to leaf color and structural attributes. However, different studies have shown that L-band SAR data have better sensitivity to secondary regrowth than Landsat (Yanasse, 1995). Further work to refine the relationships between radar backscatter and/or Landsat data to regenerative stages Of tropical forest arc necessary, in particular, since the estimation of regrowth biomass and its spatial extend in the tropical rainforests are major contributing factors in understanding the global carbon budget,

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Figure Caption

Fig. 1. Map of Rondonia, Brazil with areas of deforestation spreading out on either side of BR-364 and delineated areas of primary forest, Indian reserves, national parks, national forests, and biological reserves (Newman, 1990).

Fig. 2. Landsat and SIR-C color composite images of land use and deforestation in Rondonia, Brazil. The images are co-registered and centered at 9^{o} 55'S and 62^{o} 40'W. The RGB channels for SIR-C image are LHH, LHV, CHH and for Landsat image are bands 5,4, and 3.

Fig. 3. Forest biomass regeneration after primary forest is cut down. Even after 30 years of regrowth, the secondary forest is still different in structure and total biomass from the original forest (Newman, 1990).

Fig. 4. Map of land cover types obtained from SIR-C L-band and C-band HH and HV polarizations. The map includes five classes: primary forest, secondary regrowth, disturbed forest, quebradao, and pasture/crops.

Fig. 5. Separability of vegetation types based on the bivariate analysis of radar backscatter signatures obtained over sites with known cover types in the study area. The plots symbols represent the average backscattering coefficients obtained over polygons extracted from the sites. All the SIR-C channels are used in the analysis and results are given in a) CHV-LHV, b) LHV-LHH, and c) CHV-CHH plots.

Fig. 6. The significance of multitemporal SAR data for understanding the dynamics of the. land use change in tropical forest; a) three channel color composite of the SIR-C data acquired in April and October, 1994, b) map of land cover classes obtained by using all available channels. The classes are primary forest , pasture/crops, and regrowth/disturbed.

Table 1. Radar Characteristics of the training sites for the land cover type classes at L-band and C-band frequencies. σ^0_{HH} and σ^0_{HV} are the backscattering coefficients at the two polarizations of the mode 11 of SIR-C radar, < > and *std* stand for the average and standard deviation of the backscattering coefficients over the number of pixles of the polygons of the training areas.

L-band

Class	$<\sigma^0_{HH}>$	$std(\sigma^0_{HH})$	$<\sigma^0_{HV}>$	$std(\sigma^0_{HV})$	#pixels
Primary Forest	-9.71	1.64	-13.57	1.06	2730
Old Regrowth	-1 ().59	1.60	-15.89	1.47	878
Young Regrowth	-12.86	2.53	-18.30	1.41	565
Disturbed Forest	-5.75	1.66	-13.64	0.99	956
Quebradao	-7.39	1.27	-17.52	1.50	1028
Pasture/Crops	-14.45	1.99	-23.60	2,88	780

C-band

Class	$<\sigma^0_{HH}>$	$std(\sigma^0_{HH})$	$<\sigma^0_{HV}>$	$std(\sigma^0_{HV})$	#pixels
Primary Forest	-7.09	1.41	-10.48	0.95	2730
Old Regrowth	-7.03	1.73	-9.81	1.51	878
Yell ng Regrowt h	-8.30	0.87	-11.28	0,96	565
Disturbed Forest	-6.31	1.11	-9.77	1.03	956
Quebradao	-6.97	1.27	-15.35	1.(M	1028
Pasture/Crops	-9.67	1.99	-13.49	1.25	780

'Table 2. Confusion matrix of land cover types derived from the MAP classifier. The diogonal elements of the matrix define the percentage of those pixels that has been classified into the correct class.

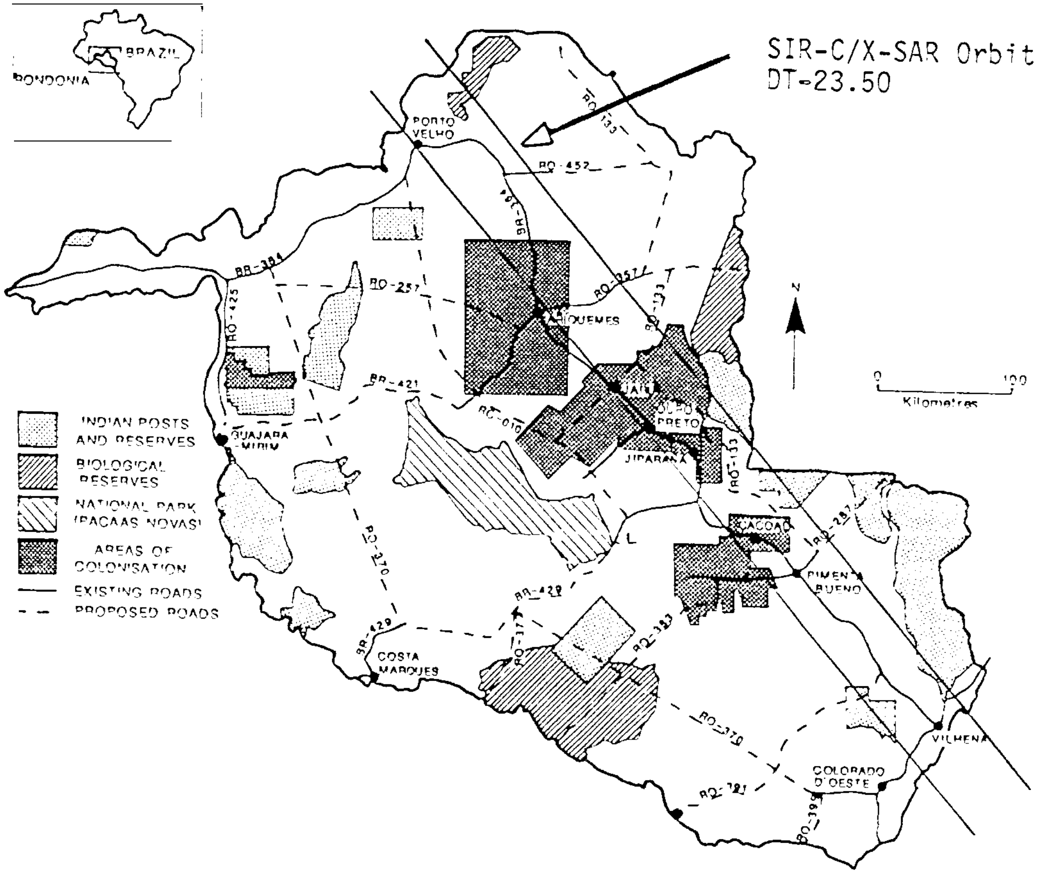
Class	PF	SR	DF	QB	PS
Primary Forest (PF)	84%	4$%	11%	()%	0%
Secondary Regrowth (S1-?)	32%	62%	0%	6%	0
Disturbed Forest (DF)	16%	()%	77%	7%	0
Quebradao (QB)	0%	8%	10%	69%	13%
Pasture/Crops (PS)	0%	?9%	0%	0%	71%

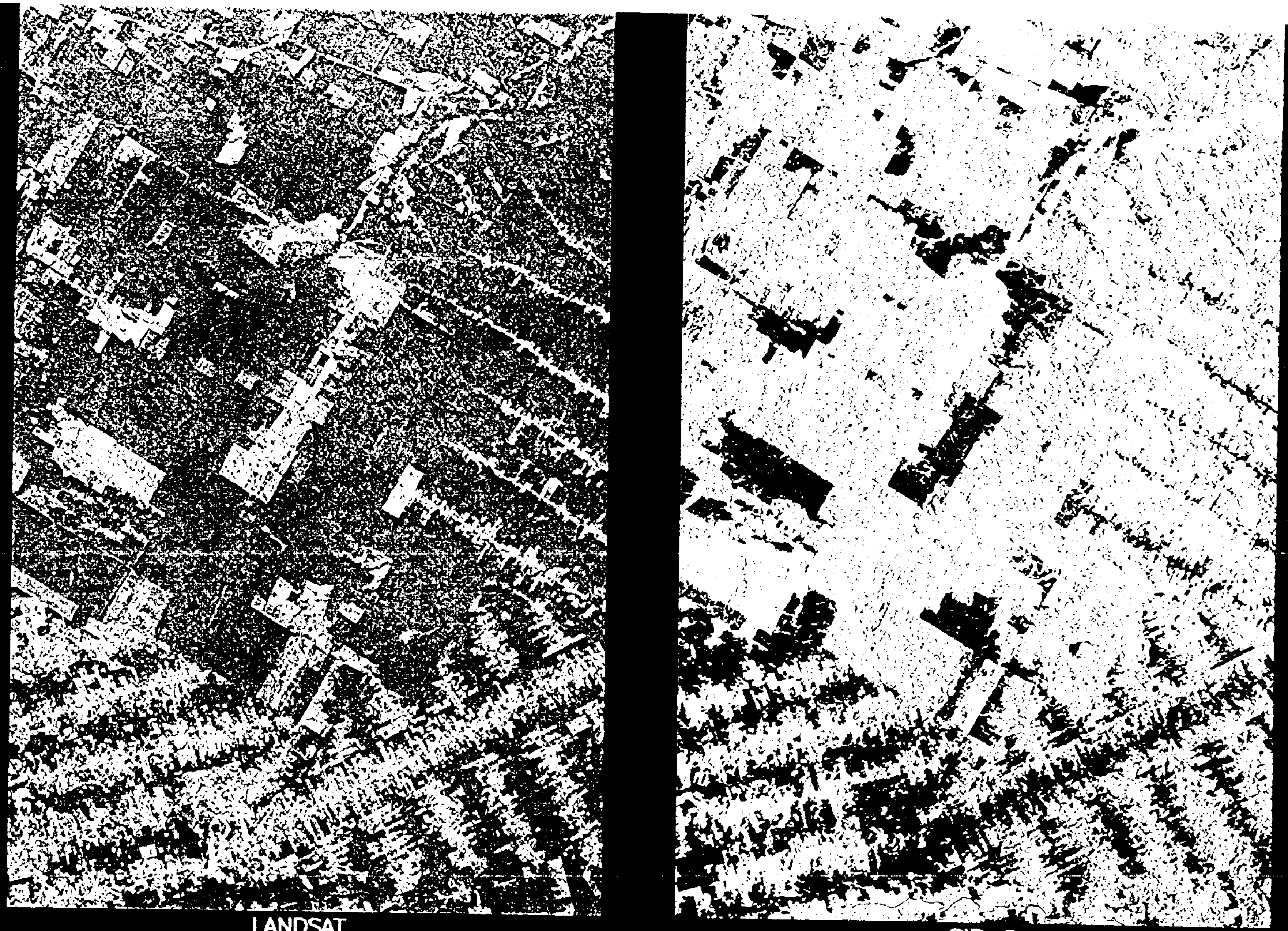
Table 3. Confusion matrix for three land cover types derived from MAP classifier. The regrowth disturbed class includes young and old regrowth arid forest disturbances, pasture/crops class includes quebradao, pasture and agricultural fields. The diogonal elements are the percentage of those pixels that has been classified into the correct class.

Class	Primary Forest	Regrowth/Disturbed	Pasture/Crops
Primary Forest	93%	7%	0%
Regrowth/Disturbed	18%	81%	1%
Pasture/Crops	0%	13%	87%

Table 4. Confusion matrix for three land cover types derived from MAP classifier using only L-band HH and HV polarizations.

Class	Primary Forest	Regrowth/Disturbed	Pasture/Crops
Primary Forest	94%	6%	0%
Regrowth/Disturbed	13%	87%	0%
Pasture/Crops	0%	5 %	95%


SIR-C/X-SAR Orbit
DT-23.50
BRAZIL
RONDONIA
INDIAN POSTS AND RESERVES
BIOLOGICAL RESERVES
NATIONAL PARK (PACAAS NOVAS)
AREAS OF COLONISATION
EXISTING ROADS
PROPOSED ROADS
PORTO VELHO
ARIQUEMES
JIPARANA
CACOAL
PIMENTA BUENO
VILHENA
COLORADO D'OESTE
COSTA MARQUES
GUAJARA MIRIM
BR-364
BR-421
BR-429
RO-257
RO-452
RO-133
RO-010
RO-370
RO-391
RO-399
RO-425
RO-429
0
100
Kilometres
N



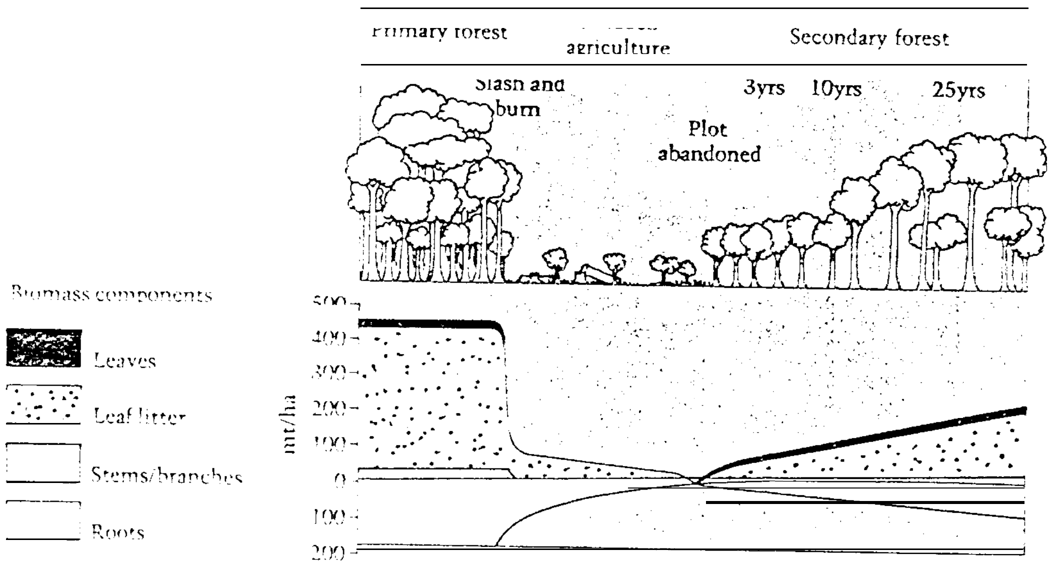
LANDSAT

RED: BAND 5 GREEN: BAND 4 BLUE: BAND 3

SIR–C

RED: L–HH GREEN: L–HV BLUE: C–HH

Figure 2



Primary forest
agriculture
Secondary forest
Slash and burn
Plot abandoned
3yrs
10yrs
25yrs
mt/ha
500
400
300
200
100
0
100
200
Biomass components
Leaves
Leaf litter
Stems/branches
Roots

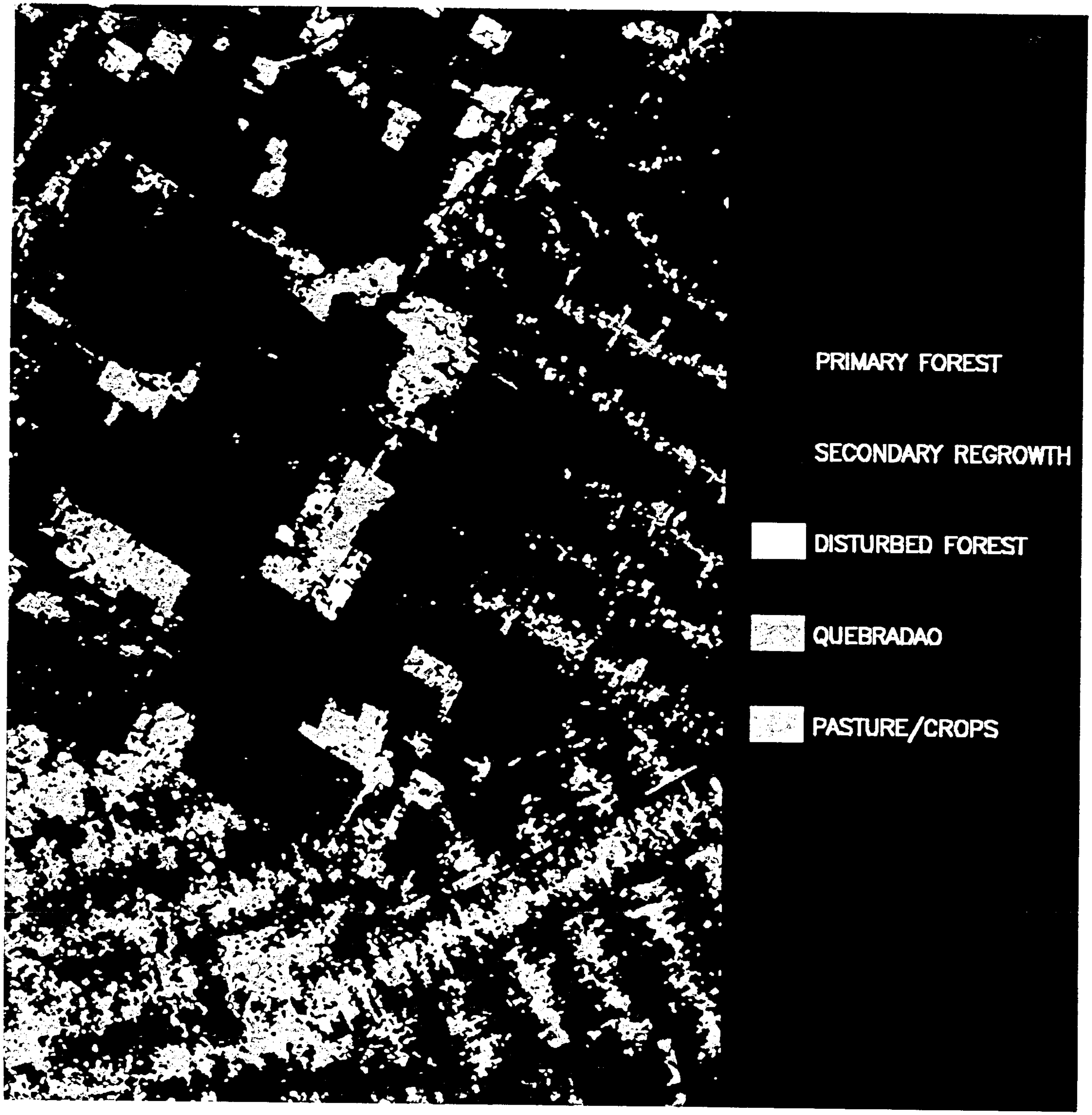
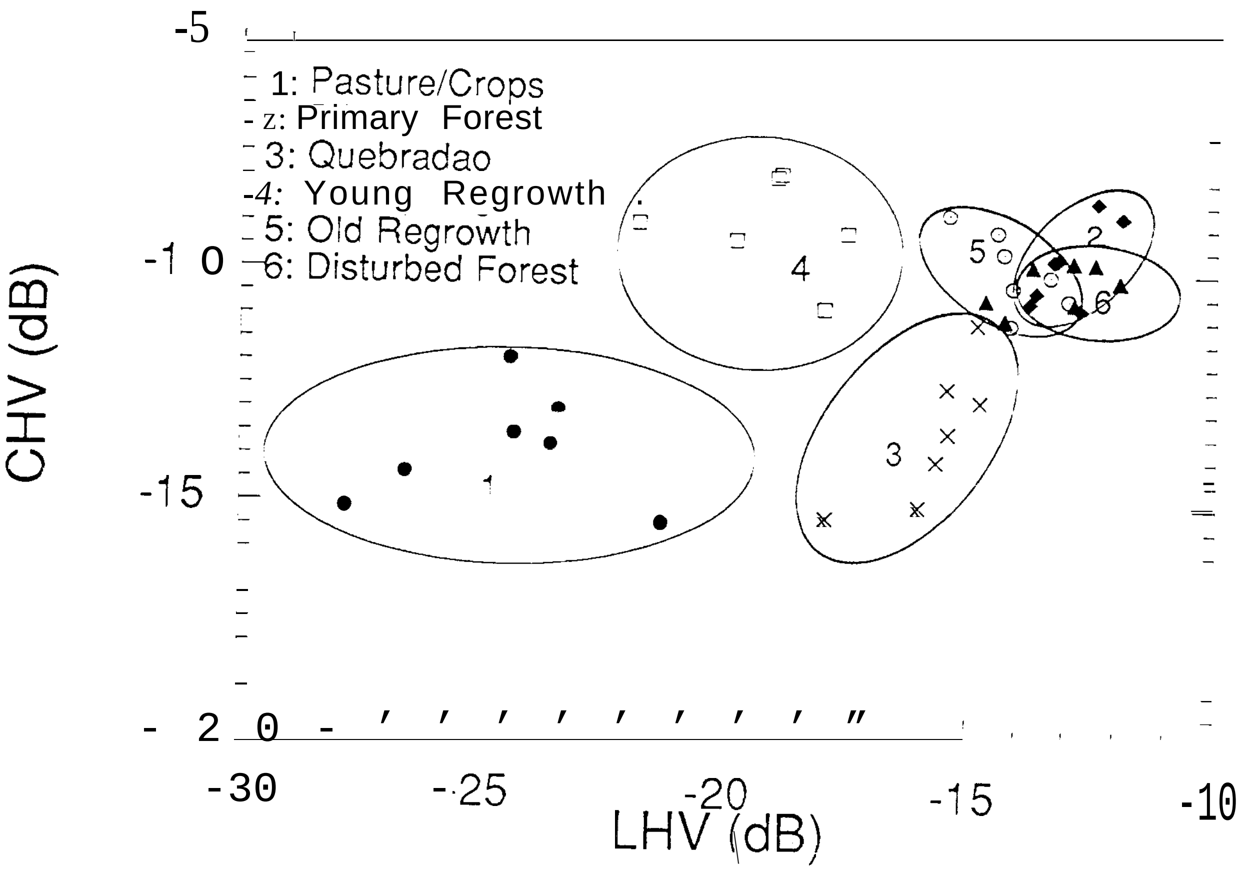
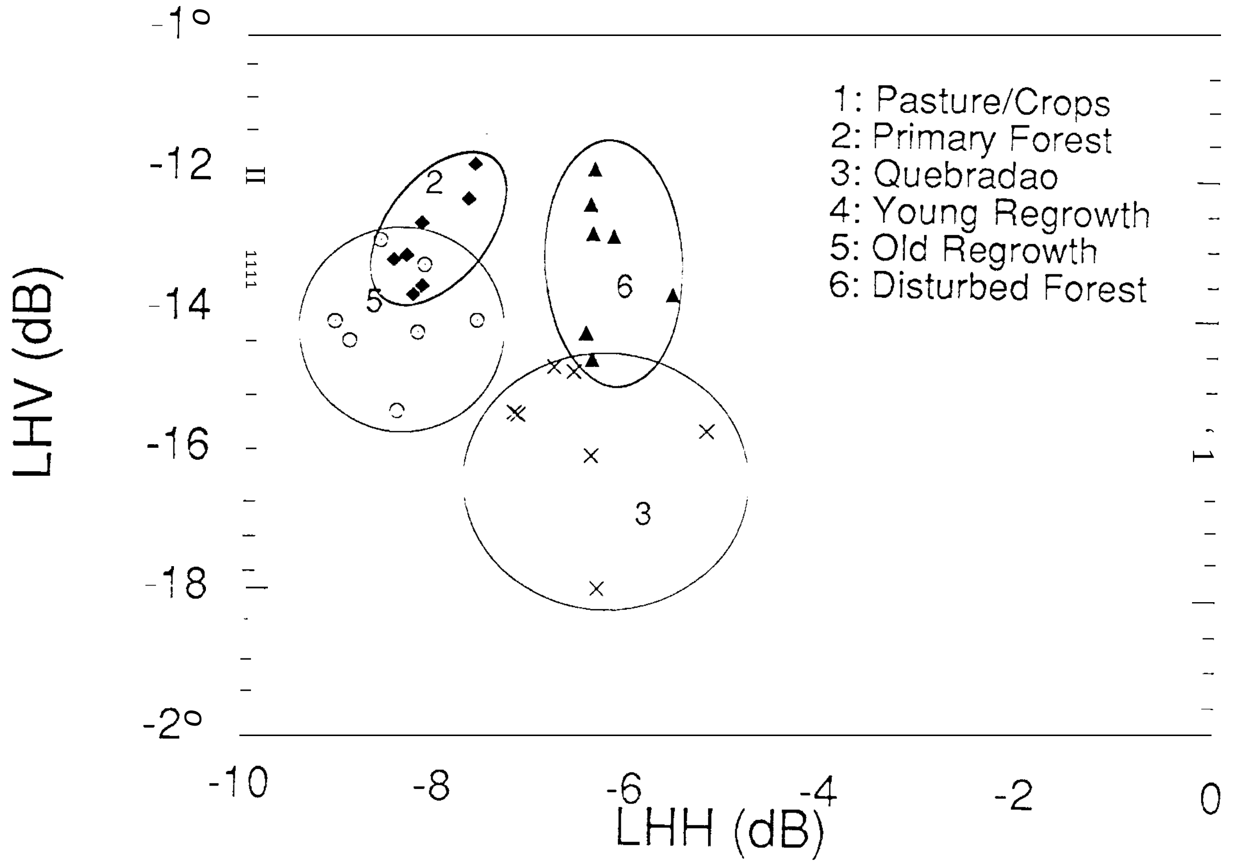

PRIMARY FOREST
SECONDARY REGROWTH
DISTURBED FOREST
QUEBRADAO
PASTURE/CROPS

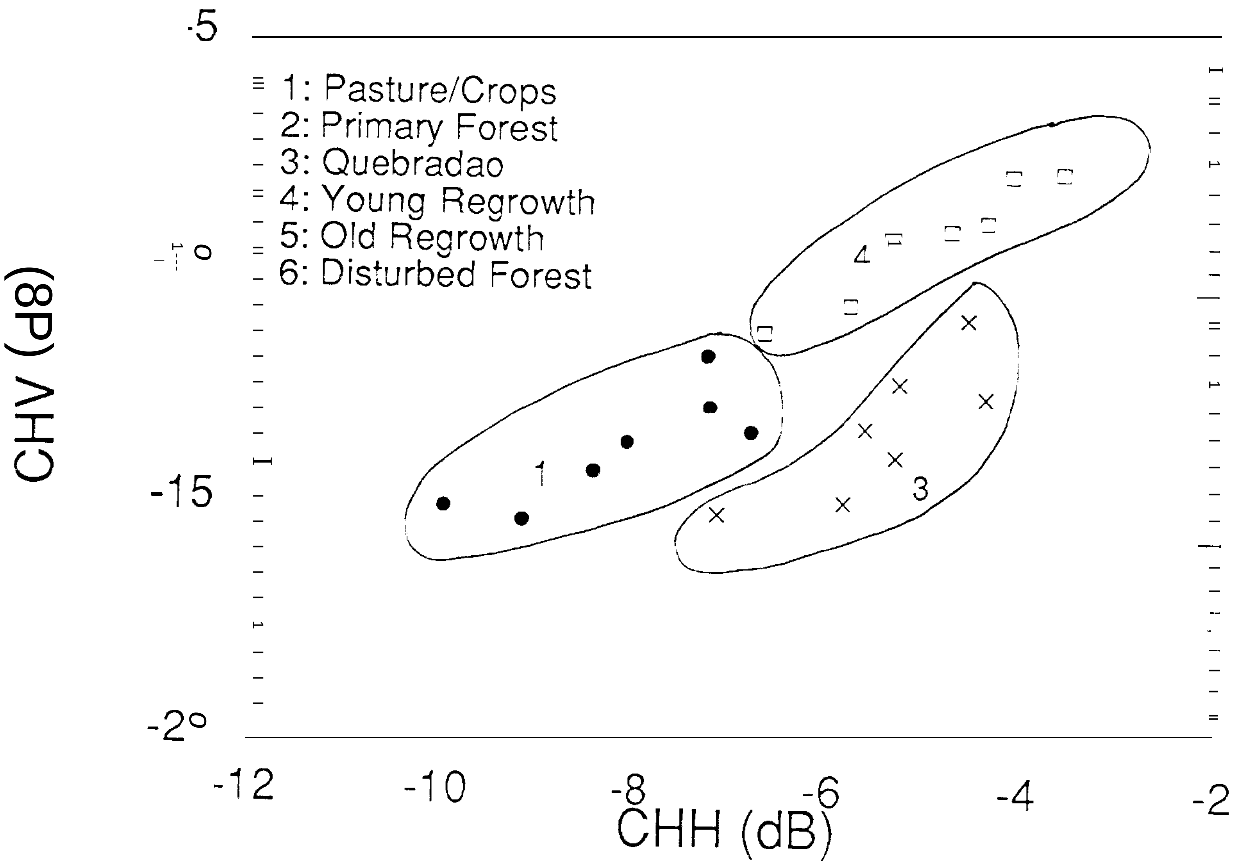
Figure 4



-5
-1 0
-15
- 2 0
1: Pasture/Crops
z: Primary Forest
3: Quebradao
4: Young Regrowth
5: Old Regrowth
6: Disturbed Forest
1
2
3
4
5
6
CHV (dB)
-30
-25
-20
-15
-10
LHV (dB)



LHV (dB)
-1o
-12
-14
-16
-18
-2o
-10
-8
-6
-4
-2
0
LHH (dB)
1: Pasture/Crops
2: Primary Forest
3: Quebradao
4: Young Regrowth
5: Old Regrowth
6: Disturbed Forest
2
5
6
3



1: Pasture/Crops
2: Primary Forest
3: Quebradao
4: Young Regrowth
5: Old Regrowth
6: Disturbed Forest
CHV (d8)
CHH (dB)
-5
-15
-2o
-12
-10
-8
-6
-4
-2
1
3
4

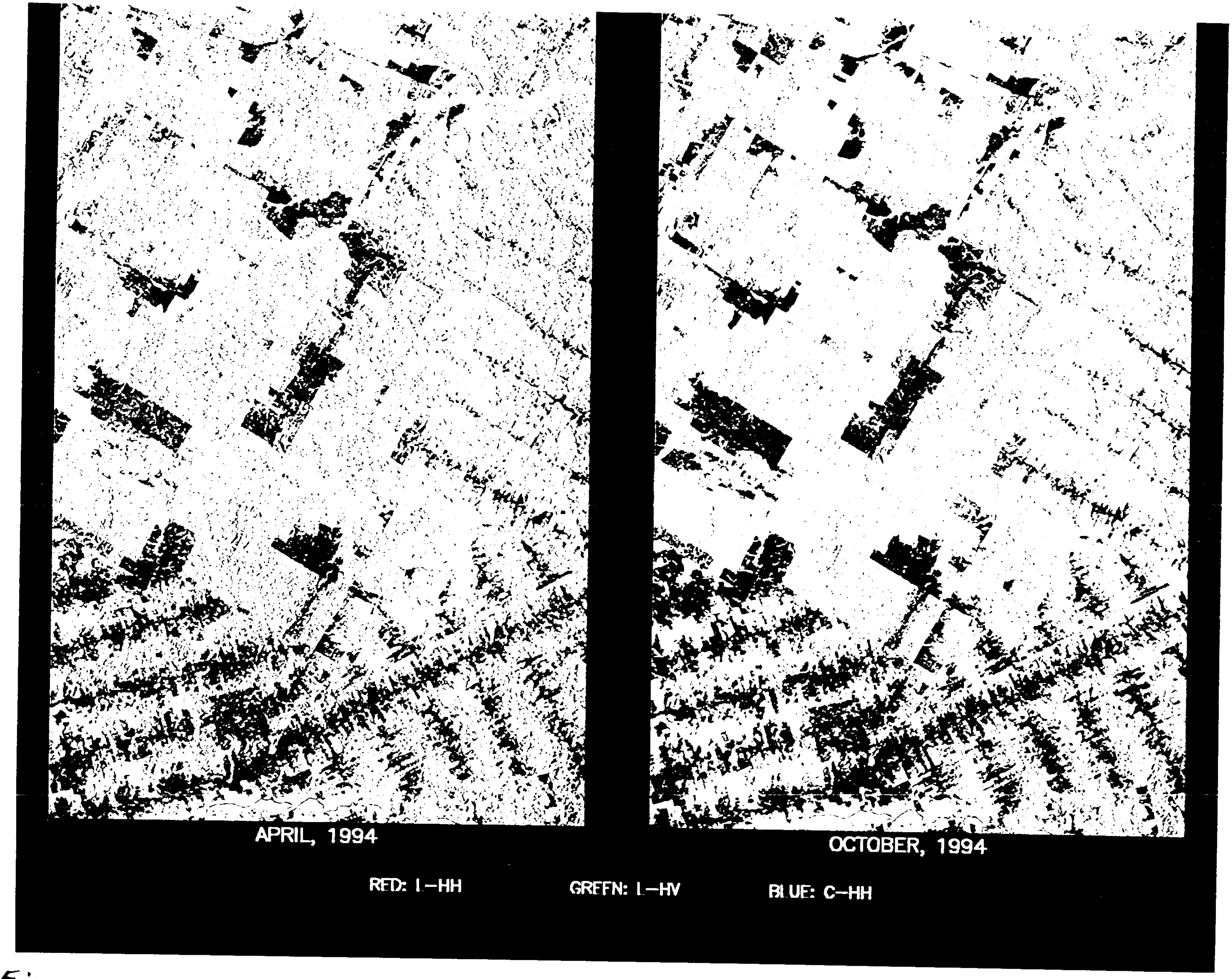
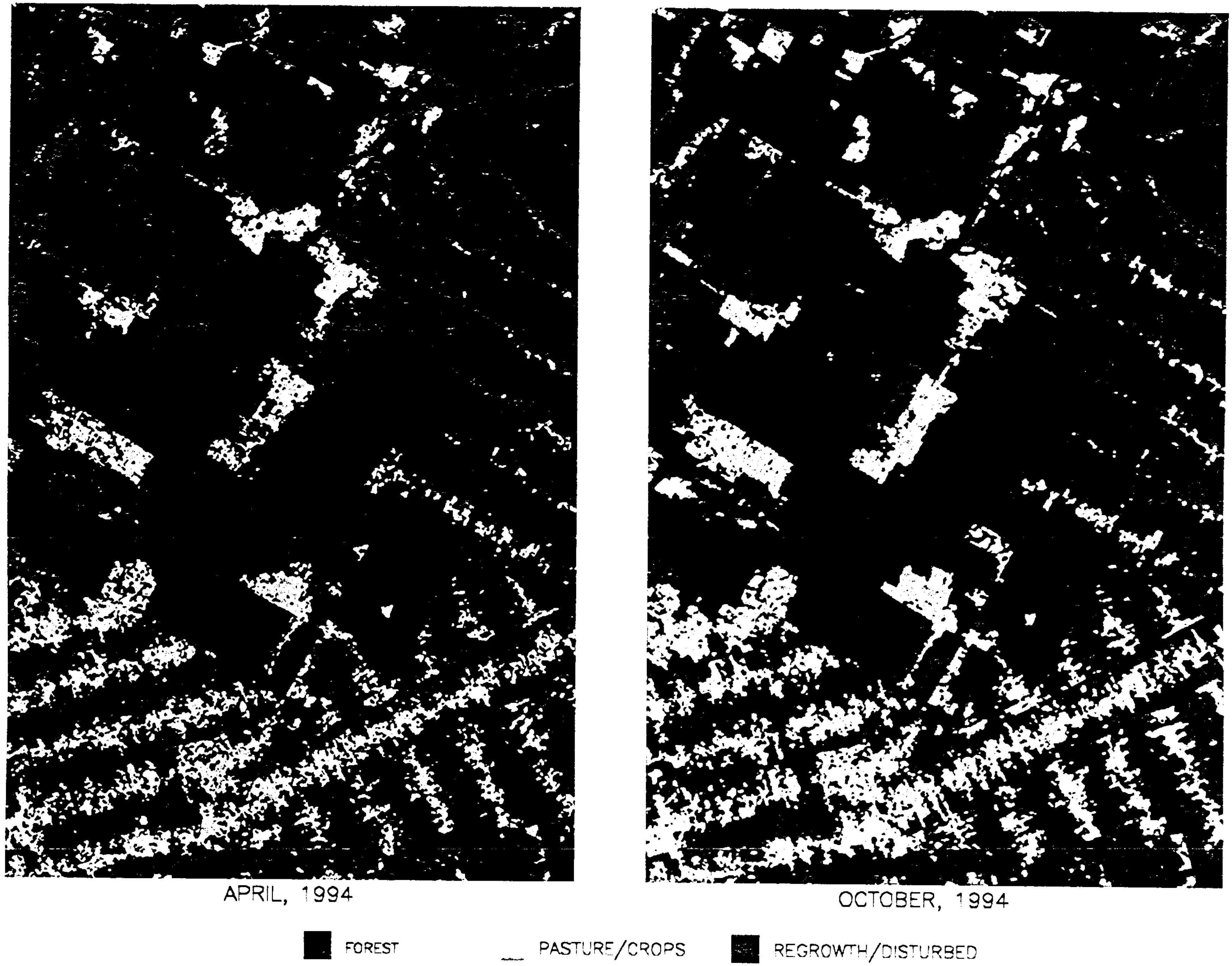


Figure 1a



APRIL, 1994
OCTOBER, 1994
FOREST
PASTURE/CROPS
REGROWTH/DISTURBED

Figure 11